

NATIONAL ADVISORY COMMITTEE
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TECHNICAL NOTE 1938

MECHANISMS OF FAILURE OF HIGH NICKEL-ALLOY
TURBOJET COMBUSTION LINERS

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SUMMARY

An investigation of turbojet combustion-chamber liners from two types of engine was conducted to determine the factors contributing to failure by cracking. Studies were made of "as-fabricated", heat-treated, and mechanically finished liners, on liners after service operation, and on liners after accelerated engine runs.

Buckling was produced at or near most cracks by thermal stresses that resulted from over-all temperature gradients and from temperature gradients at individual louvers. Cracks that formed in the buckle were probably caused principally by thermal fatigue of the buckle. Most of the cracks originated at the inner portions of the stress-relieving hole of the louvers in the upper bend of the louver flaps and probably were caused by thermal and mechanical fatigue of the flaps.

Cracking may be retarded and liner life prolonged by removing stress raisers produced by punching operations. Cracks are believed to originate both in the grain boundaries and in fissures produced by punching operations. Surface and subsurface scales of appreciable thicknesses were found at edges of metal exposed to the hot gases. Edges of cracks were lined with either or both types of scale and the subsurface scale (internal oxidation) in particular probably contributed to the cracking mechanism by forming stress raisers and subsequently lowering resistance to fatigue.

INTRODUCTION

Combustion-chamber liners used in several types of gas-turbine engine have failed both by cracking and buckling. Cracking is particularly serious because small pieces of metal have been known to break off and be carried into turbine blades causing considerable damage; both cracking and buckling disturb the air flow.

The liners used in most American engines are made of Inconel, an alloy of the following nominal chemical composition (reference 1, p. 4):

Ni	Cr	Fe	Mn	Cu	Si	C	S
78.5	14.0	6.5	0.25	0.2	0.25	0.08	0.015

This alloy is known to have good heat-resistant properties and is one of the best available for applications where flames directly contact the metal.

Although the liners used in this investigation are not of the latest design, they are considered typical of liners made with louver flaps or fins protruding into the combustion zone to introduce air for cooling purposes. Determinations of temperature conditions in liners have previously been made at the NACA Lewis laboratory. Failures were attributed to high local temperature gradients, which were as great as 700° F per inch. Most cracks occurred in the area of maximum temperature.

The investigation reported herein was conducted to determine the factors that contribute to failures in combustion-chamber liners. Such metallurgical conditions as green-rot (reference 2), sulfide penetration (reference 3), oxide penetration, and carburization were considered. Analysis of such physical conditions as the thermal stresses present in the liner was found to be necessary in completing this research.

The effects of heat treatments and of removing stress raisers from punched edges prior to operation of the liners were determined by running liners in engines and examining cracks that formed.

APPARATUS AND PROCEDURE

Liners. - Liners from two types of turbojet engine were investigated. They are designated type A and type B (fig. 1). The type-A liners had cracked in service and had been removed from the engine for this reason. The history of these liners was unavailable, but it was known that an unleaded fuel, probably AN-F-32, was used in their operation. An "as-fabricated" type-A liner was also examined. Type-B liners were run in an engine of the type shown in figure 2 in a cyclic "accelerated-life" run under the following conditions:

Duration (min)	Duration (sec)	Rotor speed (rpm)	Gas temperature at exhaust-cone outlet (°F)
4	30	4000 ±50	1100 max.
0	15	Acceleration to 11,500	1450 ±50
15	0	11,500 ±50	1240 ±20
0	15	Deceleration to 4000	1260 max.

The sulfur content of AN-F-32 fuel purchased for the investigation varied from 0.011 to 0.044 percent.

Three groups of type-B liners were examined. The first group was run for 66 hours and 57 minutes in an engine used in cyclic tests. The liners became so severly cracked that four of them were removed for examination. The other two groups of liners were modified by heat-treating and mechanical finishing in attempts to reduce failures and were run for 16 hours and 40 minutes.

Metallurgical examination. - The metallurgical examination primarily consisted of visual and metallographic studies of type-A liners that failed in service and type-B liners that had been run in the accelerated-life determinations for 66 hours and 57 minutes.

These liners were visually examined for size, shape, and origin of cracks, for scale patterns that indicate temperature gradients in the metal, for carbonaceous deposits, and for buckling or warping. A large number of cracks were metallographically studied at high magnifications. Small sections that contained cracks were removed from the liner, mounted in plastic, and polished with special precautions to preserve edges and scale formations. In general, three areas of the microspecimens were examined both etched and unetched: (1) cracks and adjacent areas, (2) punched edges, and (3) areas away from surfaces exposed to the gaseous atmospheres. The cracks were examined for intercrystalline and transcrystalline characteristics, scale formations, and possible oxidant penetration of the metal prior to crack formation. The three areas previously mentioned, particularly the punched edges, were checked for evidence of mechanical working, the presence of stress raisers in the form of tears, or fissures, microstructural abnormalities, precipitation of carbides in grain boundaries and within grains, carburization, and grain size.

Microspecimens from the as-fabricated type-A liner and from a type-B liner, run for 16 hours and 40 minutes, were also studied. The specimens from the type-A liner were examined to determine the initial condition of punched edges prior to use, and the specimens from the type-B liner were examined to determine whether the cracks began in an intercrystalline or transcrystalline manner.

The samples were examined with a research metallograph and several auxiliary measuring eyepieces, such as a filar micrometer eyepiece that could measure distances down to a few hundred thousandths of an inch, and a grain-size measuring eyepiece.

Production of thermal gradients in type-B liner. - An acetylene flame was used to produce hot zones and temperature gradients in a liner similar to those formed in the liners during engine operation. The oxide patterns formed on the liners run for almost 67 hours were used to indicate the temperature patterns that should be produced with the acetylene flame. In order to determine whether failures similar to those found in liners could be reproduced in short periods of time by artificially creating temperature gradients, the following experiments were made:

1. A thermal gradient was first produced by heating a louver flap and the surrounding metal for 1 minute to a maximum temperature of approximately 1700° F and cooling the portion immediately downstream of the louver with an air blast. The temperatures were estimated from visual observation and the area was examined for buckling and cracking.
2. The zone previously heated was then alternately heated and cooled 30 times and again examined.
3. The upstream portion of the louver in the same zone was then heated to a maximum temperature of approximately 1900° F and the entire downstream portion was air-cooled. This procedure was followed twice, the time of heating in each case being about 2 minutes.
4. Several louver flaps were then alternately heated from the inside of the liner to about 1600° F and air-cooled. Motion of the flaps during the thermal cycle was observed.

Chemical analysis. - An attempt was made to scrape corrosion products (scale) from the liner surfaces in order to determine the presence of sulfur. Samples large enough for chemical analysis could not be obtained, however, because the scale was both thin and tight. Analyses by X-ray and electron diffraction of the scale were attempted but no conclusions could be drawn from the data. The results seemed to indicate that oxides were present; however, positive identification of individual oxides was impossible with the techniques used. A large number of similar oxides and isomorphs, which may form from the alloying elements in Inconel, made the identification difficult. Carbon deposits, which were as thick as $1/16$ inch and were present in all the liners, were scraped and sent to the National Bureau of Standards for quantitative chemical analyses for carbon and sulfur. In addition, a spectrographic analysis of the deposits was made.

Heat treatments and mechanical finishing. - In order to determine if heat-treating would improve the resistance of Inconel liners to cracking and if engine runs involving heat-treated liners were warranted, preliminary investigations were made. Trial specimens were treated at 900° , 1600° , and 2200° F, air-cooled and water-quenched, examined metallographically, and hardness tested. The specimens were made of $1/32$ -inch dead soft Inconel and $5/8$ -inch holes were punched in them so that in addition to examining the general microstructure, the punched edges could be checked for distorted grains and the changes that the heat treatments produced. A specimen that was not heat-treated was used as a standard for comparison.

The 900° F heat treatment was recommended to give this alloy spring properties and also the best resistance to fatigue and high-temperature exposure (reference 1, p. 6). The 1600° F heat treatment was expected to soften the alloy by agglomerating precipitates and relieving stresses, whereas the 2200° F treatment was expected to be a solution treatment and to increase grain size.

Because the microstructural differences found in the trial specimens were significantly great, three type-B liners were selected from stock and were heat-treated in a neutral atmosphere at 900° F for 1 hour and air-cooled, at 1600° F for 2 hours and air-quenched, and at 2200° F for 2 hours and air-quenched.

The atmosphere was produced from propane, which had a sulfur content of 0.005 percent. After each sample, except the one treated at 900° F, had been held at temperature for the required time, it was quickly placed in a cylindrical furnace and air-quenched with a blast of air from all sides.

Three additional type-B liners were heat-treated at these same temperatures. Before being heat-treated, however, the punched holes were reamed, sanded, and vapor blasted. An additional liner was also mechanically finished but not heat-treated.

Reaming, sanding, and vapor blasting was employed because information from the metallographic examinations indicated that service life might be improved by removing the roughness of the edges produced by punching. The procedure was as follows: All air-intake holes and all louver holes were reamed by hand. The air-intake holes were large enough to sand by hand but the louver holes had to be vapor blasted. Vapor blasting is very similar to sandblasting, the chief difference being that the abrasive particles are suspended in a liquid rather than in air. The reaming and the sanding removed a few thousandths of an inch of metal from the holes. Vapor blasting was intended to smooth the edges by a cutting action or by hammering shut the microscopic fissures.

These seven liners were then installed in an engine with ordinary liners spaced between them. The engine was run for 25 cycles of the accelerated-life run (a total of 8 hr and 20 min), after which all the liners were removed and inspected for cracks. The position and the length of each crack and notations about buckling were recorded. The engine was reassembled and run for 25 more cycles and the inspection procedure was repeated.

The reaming, sanding, and vapor-blasting treatment seemed to improve the resistance of the liners to cracking and therefore a new set of 14 as-fabricated liners was selected to verify the results. Seven of these liners were reamed, sanded, vapor blasted, and installed with ordinary liners in alternate positions. The engine was run for 25 cycles and the liners inspected for cracks. The data previously described for the first trials of this type were again recorded. The engine was then run again for 25 cycles and the liners were reinspected.

RESULTS

General description of macrocracks. - Almost all cracks started from the stress-relieving holes of the louvers. The two most common types of crack are shown in figure 3. (See also fig. 4.)

These cracks originated in the upper bend of the louver flap at the inner edges of the stress-relieving holes (fig. 3(a), point 1). They proceed in a direction approximately perpendicular to the holes for a distance of 1/32 to 1/16 inch. The cracks deviate from their

straight paths at this point and turn either away from the center line of the louver or parallel to the center line, as shown in figure 3(a), point 2. The cracks proceed in a slightly crooked path but continue in the same general direction, away from or parallel to the center line, (fig. 3(a), point 3). In extreme cases, cracks extended as far as the air-intake holes. Warping or buckling takes place at or near almost every crack. In many cases, the warpage forms either a ridge or a groove between the stress-relieving holes of the louvers and the nearest air-intake holes (fig. 3(c)). Buckling is most serious in the second row of louvers from the intake end (figs. 1 and 4). The louver flaps (fig. 3(a)) do not warp.

Some of the cracks were jagged and widely separated and looked like tears whereas others were minute. The smaller cracks were usually much more crooked than the larger ones. Most of the cracks were located in the second and the third row of louvers from the intake end (figs. 1 and 4).

Surface examination and chemical analysis. - Inner surfaces of the liners contained carbonaceous deposits, which extended from the intake end downstream for approximately 5 inches in type-A liners and 8 inches in type-B liners. The thickness of the deposits varied, some large areas having 1/16-inch coatings and a few others having greater thicknesses. A very few localized areas showed green oxide spots in the carbonaceous zone. The National Bureau of Standards found the carbonaceous material to be approximately 70-percent carbon and 0.3-percent sulfur by microcombustion and combustion analyses, respectively. The spectrographic analysis by the National Bureau of Standards did not reveal any significant results. The sulfur picked up by the carbonaceous deposits is not believed to contribute appreciably to the cracking mechanism because many cracks formed in areas away from the carbonaceous deposits.

Thermal gradients in liners. - Variation in color of the surface scale permitted estimation of the metal temperature. A dull gray-black coating was found on the hottest portions, particularly the zone between the first and the third row of louvers. The louvers and the adjacent metal 1 or 2 inches upstream were colored dull gray-black whereas immediately downstream were cool areas relatively unoxidized and only slightly discolored (fig. 4). Thus, a drastic temperature gradient existed at the individual louvers. Upstream-downstream temperatures at the louvers of type-B liners were measured in another NACA investigation and differences of as much as 600° F were found to occur in the second and third rows from the intake end.

The following observations were made on the type-B specimen subjected to thermal gradients:

1. A thermal gradient produced by heating a louver flap and the surrounding metal to approximately 1700° F for 1 minute caused neither buckling nor cracking.
2. When the area was alternately heated to approximately 1700° F and cooled 30 times, a very slight buckle was formed between the louver and the air-intake holes.
3. When a slightly higher temperature of 1900° F and a more severe temperature gradient were produced in the area immediately upstream and when heating time was increased to 2 minutes, a greater degree of warping occurred. This warpage was not at all comparable in degree or shape to warpage or buckling produced in liners run in accelerated-life determinations or in service.
4. When the louver flaps were heated to approximately 1600° F and the metal downstream was kept cool, the louver flaps were bent outward, approximately halving the gap between the edge of the flap and the liner surface. Alternate heating and cooling moved the louver flap inward and outward.

Metallurgical investigation. - The type-A and type-B liners that failed in service and those that were used for long periods of time in the accelerated-life determinations were severely cracked (table I). Cracks of this type are shown in figures 5 and 6. The longer cracks were chiefly transcrystalline (fig. 7) although most of them had inter-crystalline segments. Many branches from the larger cracks were inter-crystalline.

Both surface and subsurface scales were present at most of the edges of larger cracks (figs. 8 to 10). In a few cases, branches from these main cracks appeared to be lined with nothing but surface scale (fig. 11); whereas in many cases branches seemed to be entirely of the subsurface type, (figs. 5 and 9(b)). The separation of layers of scale by metal rather than a crack in some cases leads to the observation that a tubular formation of oxides existed about some of the cracks or branches. Evidence of this type of formation may be seen in figures 5, 8, and 9(b) and a pictorial explanation of what is believed to occur is shown in figure 12. Etching sometimes changes the appearance of the scale until it appears to be a two-phase structure (fig. 10). The innermost oxidized zone turns purple and the outer portion remains a dull gray.

The punched edges, as well as all other edges exposed to the gaseous atmosphere, are covered with surface scale; very often subsurface scale is also present.

The punched edges of an as-fabricated type-A liner were bordered by a layer of disturbed and elongated grains and were torn in several places (table I and fig. 13). The fissures produced by tearing were large enough to act as stress raisers or potential sources of cracking, the largest being 0.0019 inch long.

In an ordinary type-B liner run in the accelerated-life run for 16 hours and 40 minutes, some punched edges were found to be lined with small equiaxed grains, less than A.S.T.M. grain size 8, inasmuch as the cold-worked layer formed by the punching operation had recrystallized. Small incipient cracks extended from the punched edges through the layer of fine grains (fig. 14). These incipient cracks were so wide that no definite conclusions could be drawn regarding their origin. It is possible that initial cracking, which extended into the metal deeper than the fine-grained layer, preceded from some of the fissures originally present at the punched edges. Small equiaxed grains were not found on the punched edges of the type-B liners run for 66 hours and 57 minutes in the accelerated-life runs, but distorted grains were present in a few samples. Scaling very probably removed almost all traces of original grain structure at the edges.

Quantitative microscopic comparisons of punched and cracked edges and of inner grains showed no evidence of carburization or decarburation.

Yellow intermetallic compounds were found to be scattered uniformly throughout the microstructure and, for this reason, their presence could not be correlated with the failures. Solid nonmetallic inclusions were found in the metal but no abnormal segregations of any type were noticed.

Trial heat treatments. - Heat treatment at 900° F produced no significant difference from the as-fabricated sample (figs. 15(a) and 15(b)). Heating at 1600° F caused precipitation of microconstituents, whereas heating at 2200° F dissolved most of these microconstituents (figs. 15(c) and 15(d)). In addition, heating at 2200° F softened the metal, caused grain growth, and aided recrystallization. No significant differences were observed between samples that were quenched in air or in water (table II).

Heat treatment and mechanical finishing. - The results of the thermal treatments of type-B liners indicated that the heat treatments selected were ineffective in preventing cracking. A slight improvement was noted in some of the reamed, sanded, and vapor-blasted liners that had been heat-treated. The mechanical finishing of seven as-fabricated type-B liners, however, materially reduced cracking in the accelerated-life determinations as shown in table III.

DISCUSSION OF RESULTS

The location of buckling in the zone in which temperatures and thermal gradients were apparently greatest indicate that thermal stresses of a large magnitude were induced in the metal. These stresses were a result of the following conditions:

1. Over-all temperature differentials produced in a liner during combustion. The hottest zone is between the first and the third row of louvers from the intake end of the liners.
2. Temperature gradients produced at individual louvers by secondary combustion air, which enters the louvers and cools the metal immediately downstream. An abrupt line of demarcation between hot and cold areas occurs at or near the stress-relieving holes of the louvers.

Buckling occurs between the stress-relieving holes of the louvers and the air-intake holes because of the geometry of the holes and louvers and the large temperature gradients (fig. 16). Operational conditions such as starting, stopping, and power surging, which produce thermal changes in the liner, are believed to raise and lower the buckle to some extent. The fluctuating thermal stresses thereby produced are believed to fatigue the metal thermally and to produce a crack in the buckle of the type shown in figure 3(c).

By alternately heating and cooling the louver flap, an outward and inward movement of the flap was produced. The operational conditions previously described therefore probably caused a similar motion of the flaps producing a thermal fatigue. Any bending of the louver flap would apply maximum bending stresses at the inner edge of the stress-relieving holes (fig. 3(a), point 1). Because the lower side of a flap projects into the path of the combustion gases and thus becomes hot and the upper side is cooled by the flow of secondary combustion air, tensile and compressive stresses are produced in upper and lower portions, respectively, as a result of differences in thermal expansion (fig. 17). These stresses produce the upward bending upon heating.

Mechanically produced fatigue stresses are also believed to contribute to the cracking mechanism and may result from vibrations of the engine, air flowing over the flaps, and pulsations that occur during combustion. Air flow would tend to produce a motion in the flap similar to that of a vibrating reed.

Transcrysalline characteristics of the cracks and the brittle nature of the failure are also indicative of fatigue failures, particularly because the longer, more rapidly propagated cracks have few intergranular characteristics except in the branches.

Stress raisers may be classified into two groups: those produced by fabrication processes and those formed after the liner is put into operation.

The investigation has shown the importance of stress raisers produced by the punching operations, namely, that by removing torn and worked metal from punched edges cracking is greatly retarded and liner life thereby increased. Because most cracks originate in the upper bend of the louver flaps at the inner portion of stress-relieving holes, it is possible that the working of the grains in the bend is also harmful. Surface scales, which formed during engine operation are believed not only to lengthen and widen the cracks, but to act as stress raisers at the tips. Subsurface scales, which are also found at most crack edges, are inherently harmful because by expanding the metallic lattice they act as stress raisers and lower resistance to fatigue.

The intercrysalline characteristics of many cracks or branches of cracks and the accompanying scale formations indirectly indicate that some cracks first start at grain boundaries weakened or stressed by oxide penetrations. Similarly, the improvement in resistance to cracking of mechanically finished liners indicates that other cracks originate from small fissures produced by punching operations. Because the vast majority of cracks were shown to originate in the stress-relieving holes of the louvers, however, and because bending of the flap produces maximum stresses at the stress-relieving holes, it is believed that the cracks are predominantly the result of louver-flap motion. Thermal and mechanical fatigue stresses could therefore cause cracking at the stress-relieving holes even if stress raisers from punching and scaling were not present.

SUMMARY OF RESULTS

The investigation of turbojet combustion-chamber liners to determine the factors contributing to failure by cracking yielded the following results:

1. Most cracks originated at the inner portion of the stress-relieving holes of the louvers in the upper bend of the louver flaps. They were propagated at first almost perpendicularly from the edge of the hole but then turned either parallel to or away from the center line of the louver.
2. Buckling was found at or near almost every crack and usually extended from the stress-relieving holes of the louver to the nearest air-intake hole.
3. Some of the cracks probably began in an intercrystalline manner; others are believed to originate in fissures produced by punching operations. As the cracks enlarged, they tended to become more and more transcrystalline. Most of the cracks were partly intercrystalline or had intercrystalline branches.
4. Surfaces exposed to hot gases were covered with scale. Sub-surface scale (internal oxidation) occurred at many of these surfaces, particularly the edges of cracks.
5. Neither carburization nor decarburization was detected.
6. No conclusions or correlations in regard to the mechanisms of cracking could be drawn from the grain-size measurements, the presence of intermetallic compounds, or solid nonmetallic inclusions.
7. Carbonaceous deposits absorbed a relatively large percentage (0.3 percent) of sulfur from combustion gases. The sulfur picked up by these deposits, however, did not contribute appreciably to the failure by cracking.
8. Heat treatments investigated were ineffectual in preventing cracking.

CONCLUDING REMARKS

The following observations may be made from this investigation:

1. The most common types of crack that extend from the stress-relieving holes of the louvers probably are caused by thermal and mechanical fatigue of the louver flaps.

2. Buckling, which is produced at or near most of the cracks by thermal stresses, is the result of the production of over-all temperature gradients in the liner and of large temperature gradients formed at individual louvers and air-intake holes by the entrance of secondary combustion air.

3. Cracks that form in the buckle are believed to be caused principally by thermal fatigue of the buckle.

4. Cracking may be retarded and liner life prolonged by removing stress raisers produced during punching operations by reaming, sanding, and vapor blasting the edges of the punched holes. Some cracks probably originated from small fissures produced by the punching operation.

5. The surface and subsurface scales, which formed, are believed to lengthen and widen cracks, act as stress raisers thereby lowering resistance to fatigue, and, in some cases, so weaken or stress grain boundaries that cracks originate in these boundaries.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, October 11, 1948.

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TABLE I - EXAMINATION AND COMPARISON OF CRACKED AND PUNCHED EDGES

Liner section	Type of section	Punched Edges		Specimens obtained from type-A liner		Specimens obtained from type-B liner, which failed by cracking during accelerated-life runs of 66 hours and 57 minutes		Edges of crack
		Description of punched edge ^a	Depth of deepest fissures (in.)	Thickness of scale (in.)	Thickness of scale (in.)	Approximate length of scale (in.)	Surface or subsurface scale visible	
1	Long	Louver	Smooth	.00025	.....	.....	.....	Transcrystalline or intergranular cracks
1	Long	Louver	Rough	.0017	.....	.....	.....
1	Long	Louver	Smooth	.0011	.....	.....	.....
1	Long	Louver	Rough	.0033	.....	.....	.....
1	Long	Louver	Smooth	.0023	.....	.....	.....
2	Long	Louver	Rough	0.0053	.....	0.0017	0.0005	Both
2	Long	Louver	Smooth	.....	.....	.00033	.0006	Both
2	Long	Louver	Rough	.....	.....	.0008	.0008	Both
3	Long	Near louver	Rough	0.0028	.....	0.0016	0.0002	Both
3	Long	Air intake	Rough	.....	.....	.0012	.0003	Both
3	Long	Air intake	Rough	.....	.....	.0009	.025	Both
3	Long	Air intake	Smooth	.....	.....	.0005	.25	Both
4	Cross	Near louver	Smooth	0.00032	.....	0.0001	.....	External transcrystalline
4	Cross	Near louver	Smooth	.....	.....	.00023	0.0003	External transcrystalline
4	Cross	Near louver	Smooth	0.00059	.....	.00012	0.0002	External transcrystalline
4	Cross	Near louver	Smooth	0.00025	.....	.00012	0.0008	External transcrystalline
4	Long	Louver	Smooth	0.0014	.....	.00023	0.0012	External transcrystalline
5	Long	Center tail	.....	.....	.....	0.00017	0.031	Both
5	Long	Air intake	Rough	0.0117	.....	0.0005	0.006	Both
5	Long	Air intake	Rough	.0100	.....	.00028	.0003	Both
6	Long	Louver	Smooth	0.00032	.....	0.00028	0.0003	Chiefly transcrystalline
6	Long	Louver	Smooth	0.00036	.....	0.00117	0.00036	Chiefly transcrystalline
6	Cross	Louver	Smooth	0.00030	.....	.00023	0.00017	External transcrystalline
6	Long	Louver	Smooth	.....	.....	.0012	.00035	External transcrystalline
6	Long	Louver	Smooth	.....	.....	.0021	.00058	External transcrystalline

^a Cross, cross or transverse section perpendicular to rolling direction.
^b Long, longitudinal section parallel to rolling direction.

^c Rough edge, edge which appears jagged or irregular at a magnification of X200 and was caused by punching or by corrosion. An edge is considered rough if several small cracks or tears are present. If one or more large cracks are present they are not considered. Smooth edge, edge that appears smooth at X200.

^d Depth of deepest fissures, applies only to mechanical tears or jaggedness at punched edges and does not apply to main cracks.

^e Depth of working, grains at punched edges are elongated or worked. This elongation is noticeable at high magnifications because normal grains of metal are equiaxed. Distances from the edges inward in which elongated grains are found constitutes depth of working. Average measurements rather than maximum or minimum extremes were made with a research metallograph and filar micrometer eyepiece.

^f Thickness of scale, scale was measured on an area, that was least disturbed by polishing. Average thicknesses, rather than maximum or minimum were recorded. The purpose was to obtain approximate measurements. Where both surface and subsurface scales were present, the combined thicknesses were measured.

^g Not punched, exposed surfaces (side edges).



TABLE II - VARIATION OF MICROSTRUCTURE AND HARDNESS OF INCONEL SHEET WITH HEAT TREATMENT

Sample	Heat treatment	A.S.T.M. grain size	Etching time in 10-percent sodium cyanide (electrolytic) (min)	Range of Rockwell R30T superficial hardness (from superficial values)	Description of microstructure
1	Dead-soft stock	3-7	10	61-62	Grains at edges are worked to approximate depths of 0.001 to 0.002 inch. Boundaries contain fine solid precipitates and some globules. Interior grains are equiaxed (fig. 16 (a)).
2	Annealed at 900° F for 1 hour, air-cooled	5-7	15	58-61	Same as sample 1 (fig. 16 (b)).
3	Annealed at 1600° F for 2 hours, air-cooled	6-8	5	61-62	Grain boundaries at edges of punched hole are channeled and show mechanical working. Slight evidence of grain growth exists at edges. Grain boundaries and grains contain a large number of solid and globular precipitates (fig. 16 (c)).
4	Annealed at 1600° F for 2 hours, water-quenched	4-8	45	59.5-62.5	Same as sample 3.
5	Annealed at 2200° F for 2 hours, air-cooled	1-4	30	48-51	47.5-52 Grains are not larger at punched edge as would be expected. Grain boundaries are very difficult to etch because there are almost no visible precipitates (fig. 16 (d)). Tight scale was formed on edges.
6	Annealed at 2200° F for 2 hours, water-quenched	3-5	45	52-53.5	53.5-55.5 Same as sample 5.

^aSmall hole drilled through the specimens caused an irregular current density and an abnormal etching time.



TABLE III - EFFECTS THAT REAMING, SANDING, AND VAPOR
BLASTING OF PUNCHED EDGES HAVE UPON CRACKING

Time in accelerated life runs		Average number of cracks in seven as-fabricated liners	Average number of cracks in seven reamed, sanded, and vapor-blasted liners
(hr)	(min)		
8	20	8.43	1.86
16	40	20.29	9



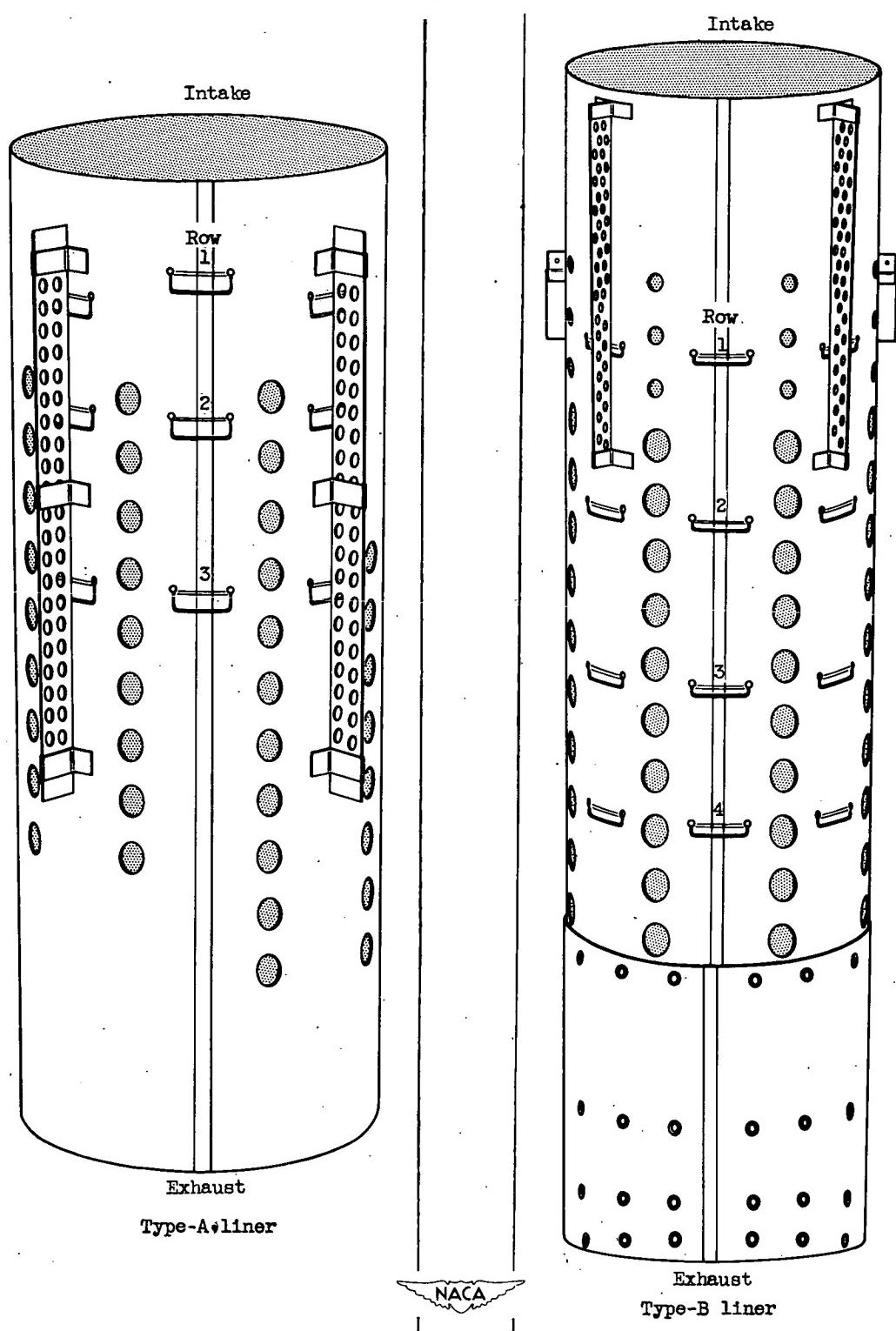


Figure 1. - Combustion-chamber liner investigated.

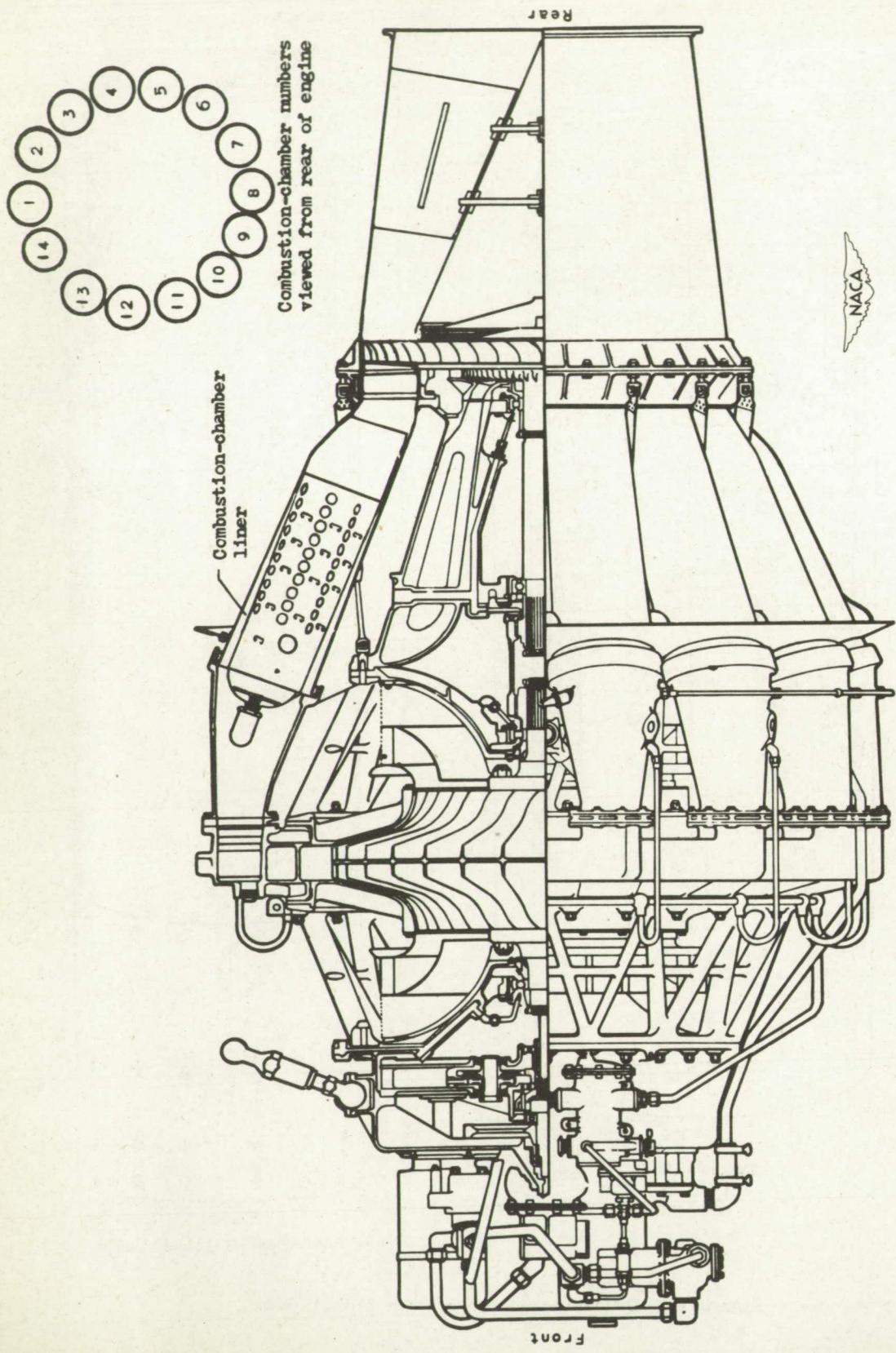
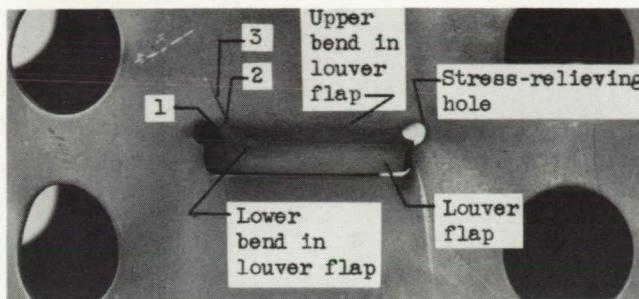


Figure 2. - Turbojet engine showing typical type-B combustion-chamber liner installation.

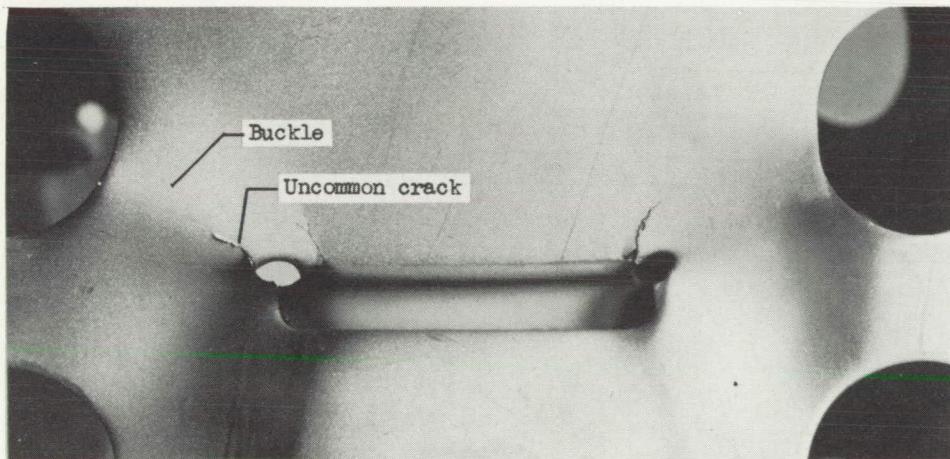


(a) Most common type of crack.



(b) Second most common type of crack.

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(c) Large buckle and typical cracks enlarged from figure 4.

Figure 3. - Typical cracks and buckle at louver.

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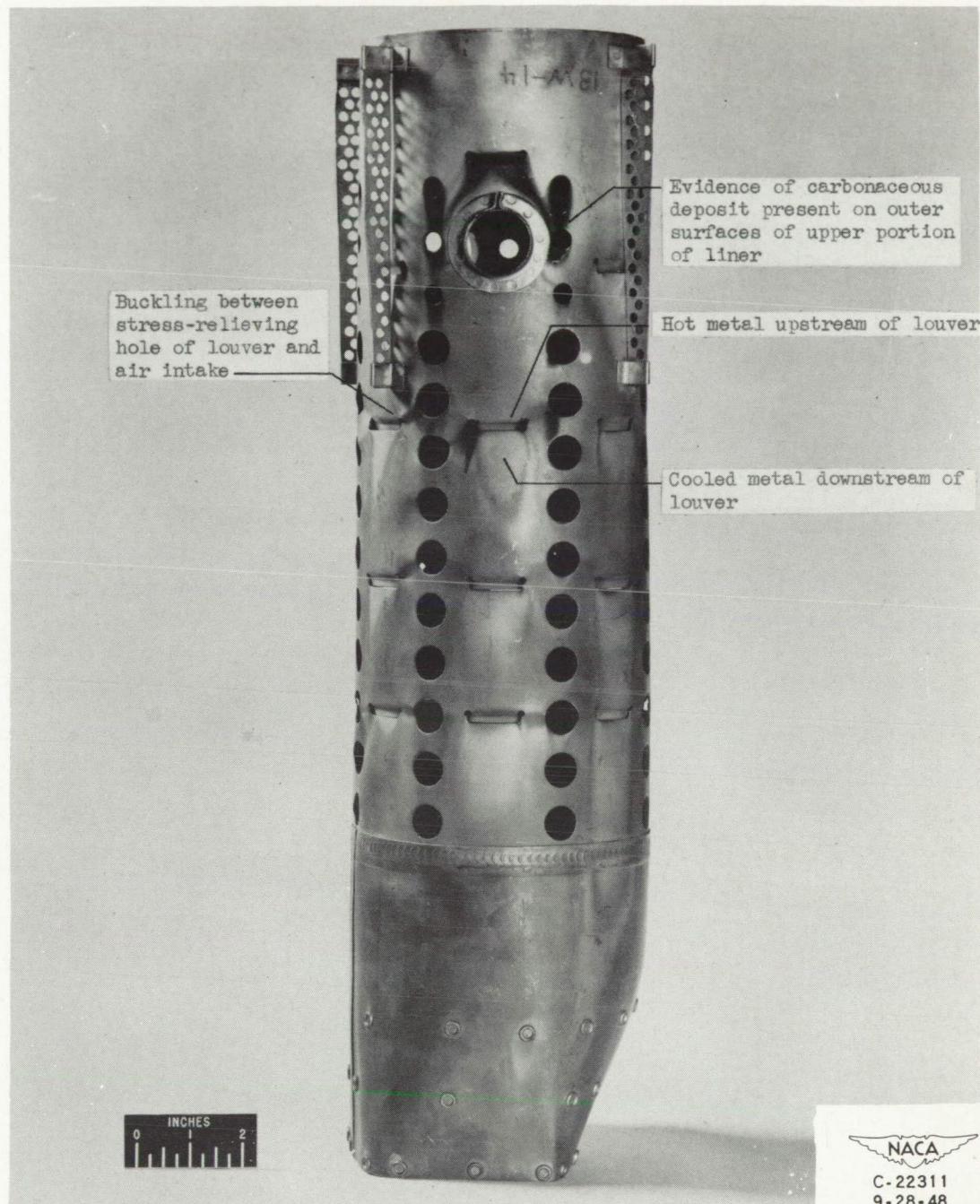


Figure 4. - Combustion-chamber liner showing cracks extending from louver holes.

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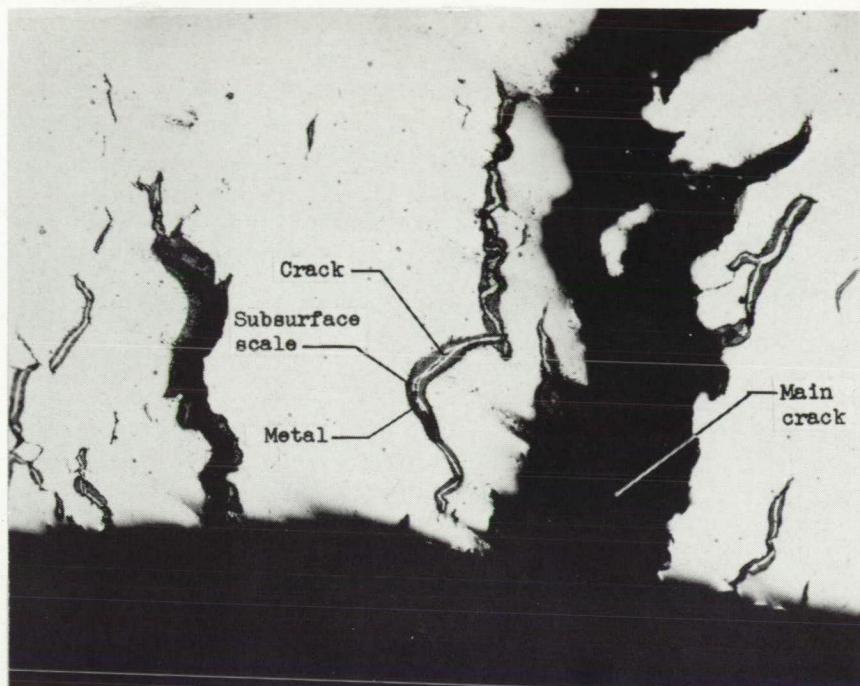


Figure 5. - Cracks at edge of air-intake hole. Type-A liner; etchant, none; condition, failed in service; magnification, X100. Largest crack is approximately 1/4 inch long.

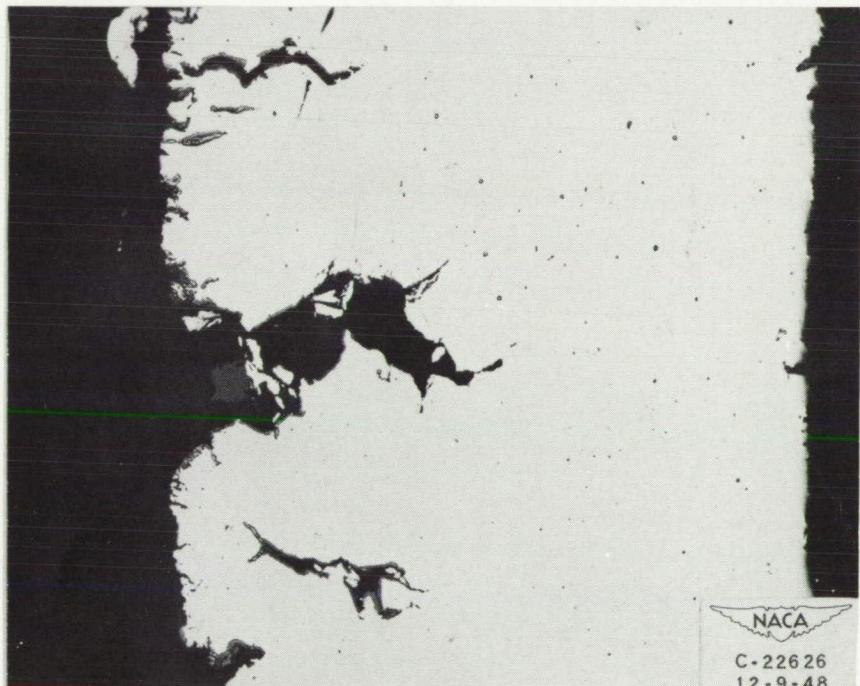
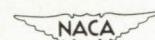
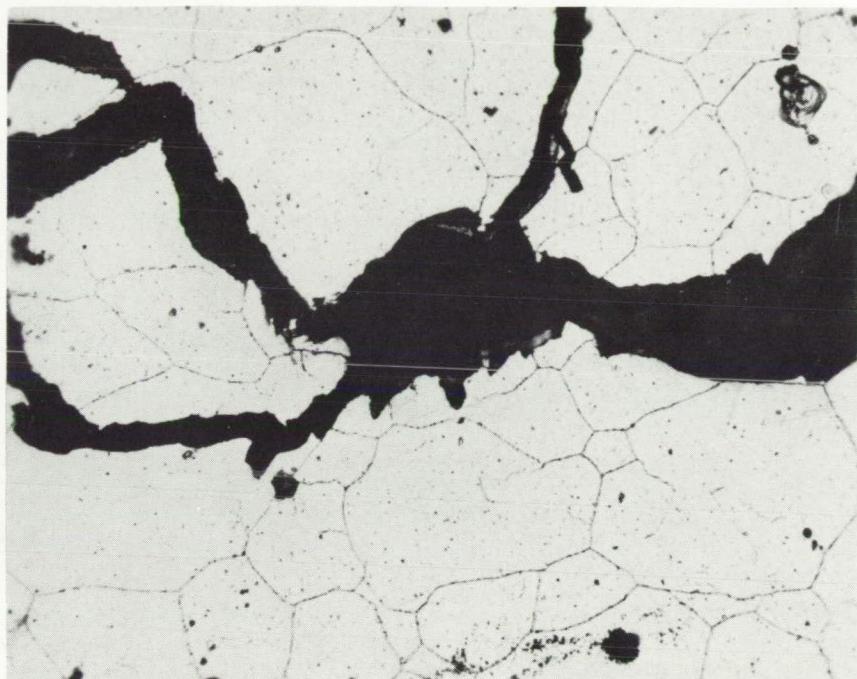


Figure 6. - Cross section showing cracks extending into metal from liner surfaces. Type-A liner; etchant, none; condition, failed in service; magnification, X100. Cracks shown were located near large crack.

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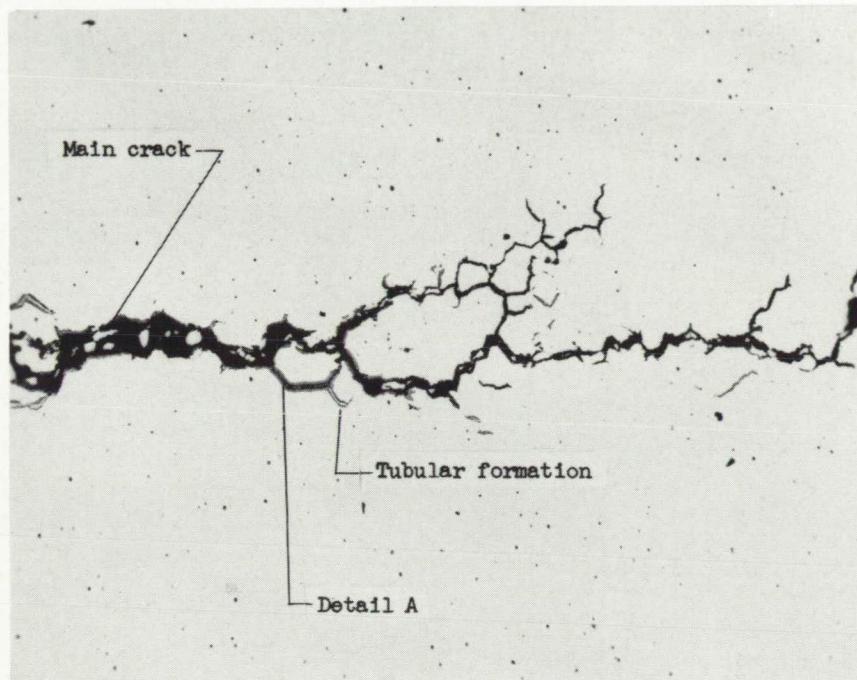
The NACA logo, which consists of the letters "NACA" in a bold, sans-serif font, enclosed within a stylized winged emblem.

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Figure 7. - Transcrysalline cracking in liner run for 66 hours and 57 minutes. Type-B liner; etchant, 5-percent aqua regia in water, electrolytic; magnification, X350.

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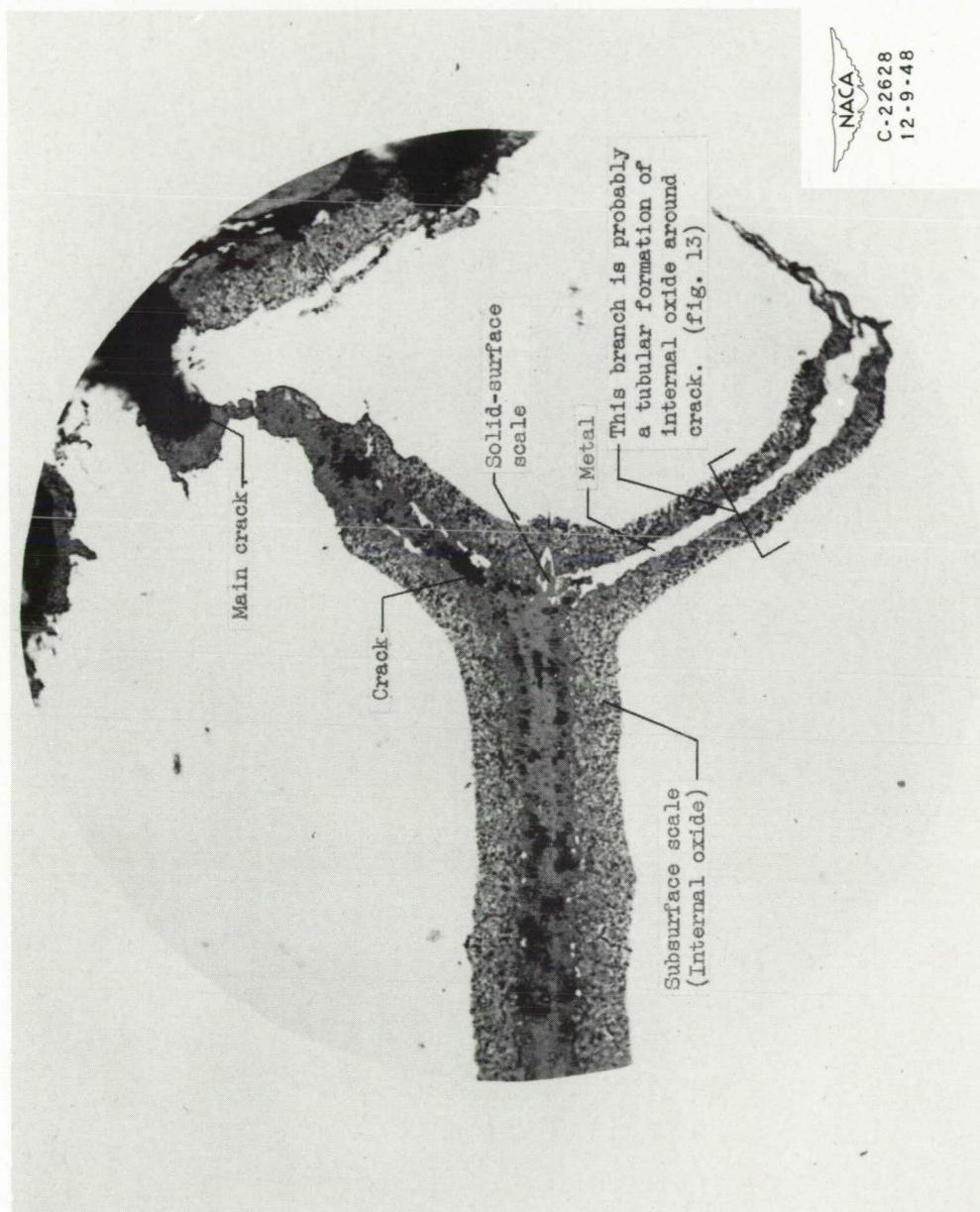
(a) Magnification, X60.

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Figure 8. - Portion of large crack showing surface and subsurface scale. Type-A liner;
etchant, none; condition, failed in service.

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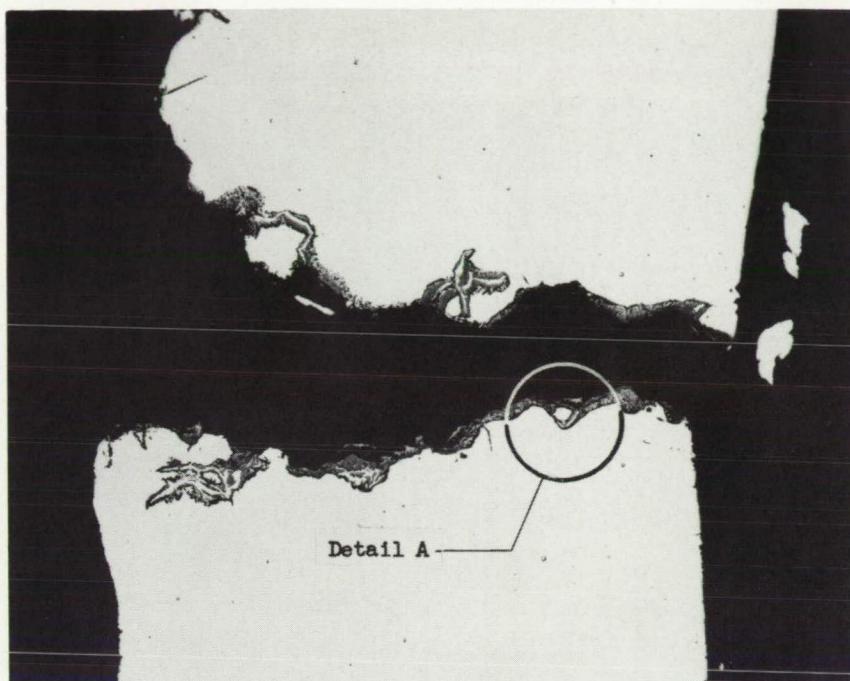
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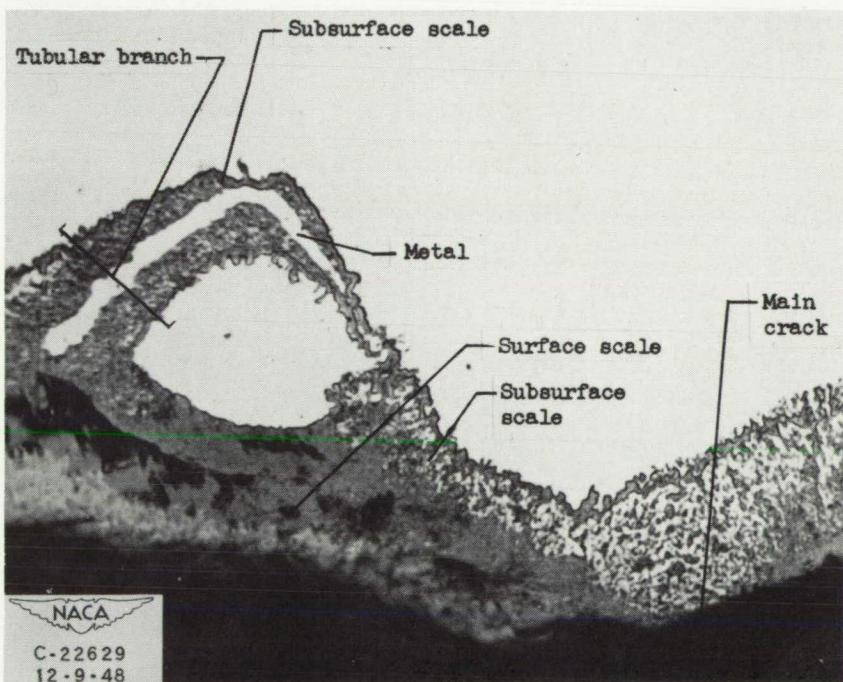
(b) Detail A; magnification, X1500.
Figure 8. - Concluded. Portion of large crack showing surface and subsurface scale. Type-A liner; etchant, none; condition, failed in service.

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(a) Cross-sectional view; magnification, X100.



(b) Detail A showing surface scale at edge of crack; magnification, X1500.

Figure 9. - Crack extending from punched edge. Type-A liner; etchant, none; condition, failed in service.

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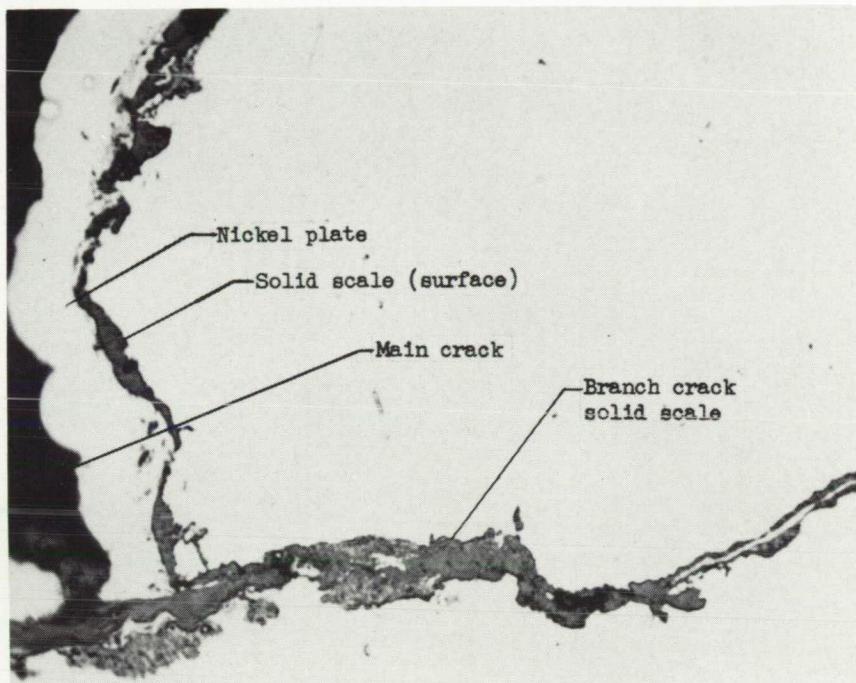
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Figure 10. - Scale formations at crack. Type-B liner; etchant, 5-percent aqua regia in water, electrolytic; condition, cracked during accelerated-life determination; magnification, X500. Etchant has darkened subsurface scale zone. Scale almost appears to be two-phased because dark zone is dull purple and surface scale is gray.

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Figure 11. - Branch of main crack. Type-B liner; etchant, none; condition, cracked during accelerated-life determination; magnification, X1500. Scale appears to be solid, similar to surface scale. Edge of main crack is plated with nickel.

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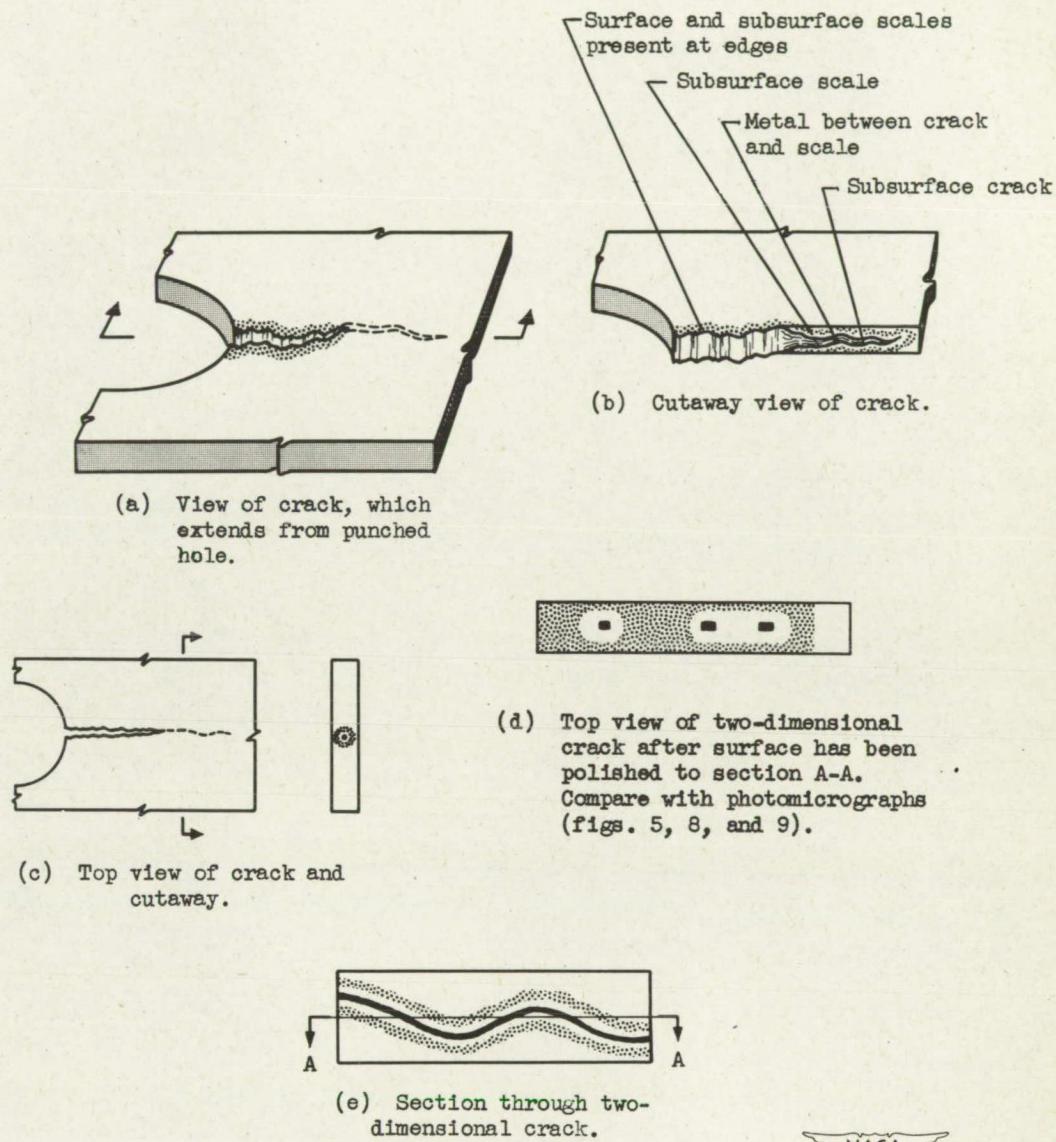
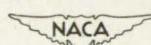


Figure 12. - Pictorial explanation of tubular formation.



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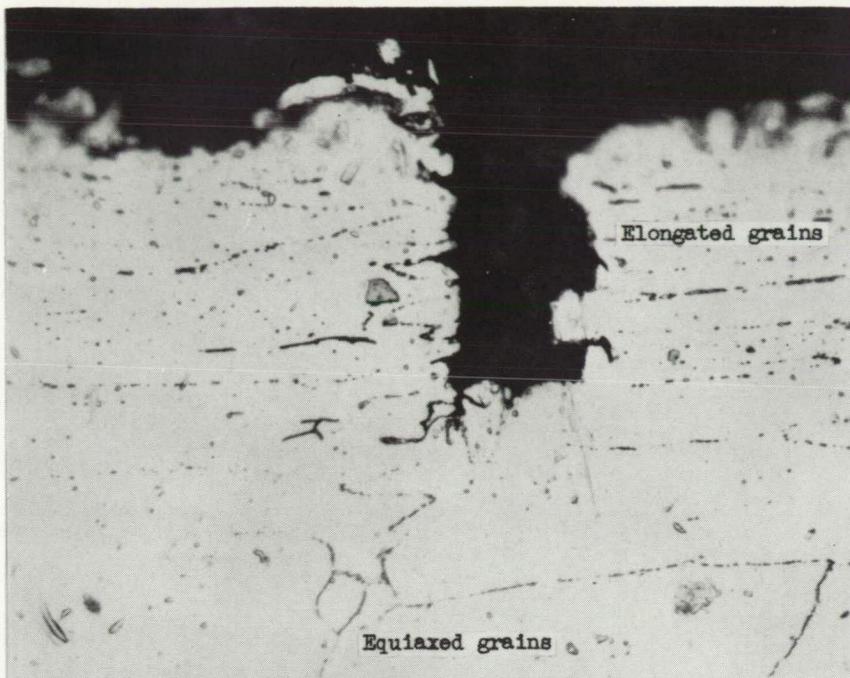


Figure 13. - Edge of stress-relieving hole of louver. Type-A liner; etchant, 10-percent sodium cyanide, electrolytic; condition, as fabricated; magnification X750. Note fissure and elongated grains. Fissure is 0.0019 inch deep.

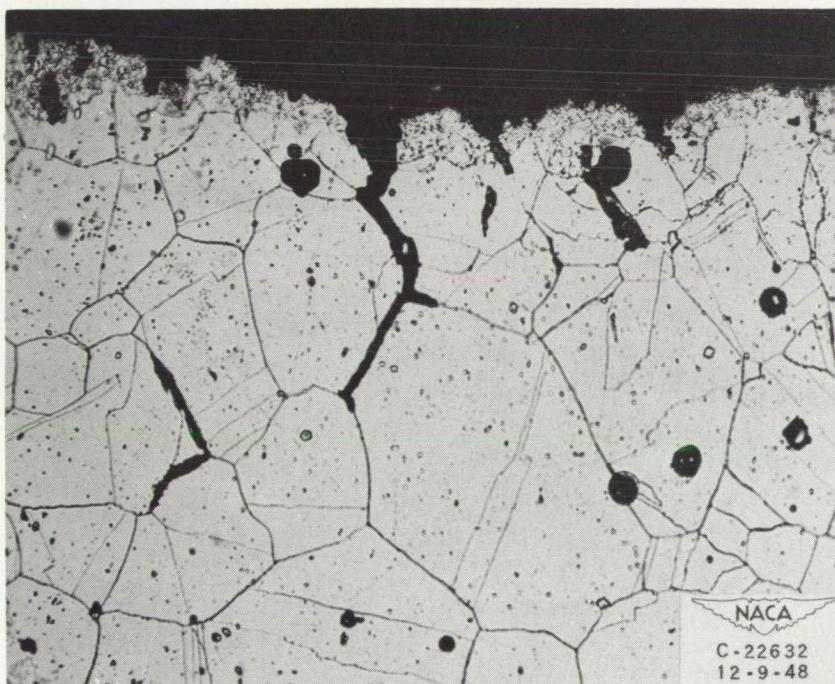


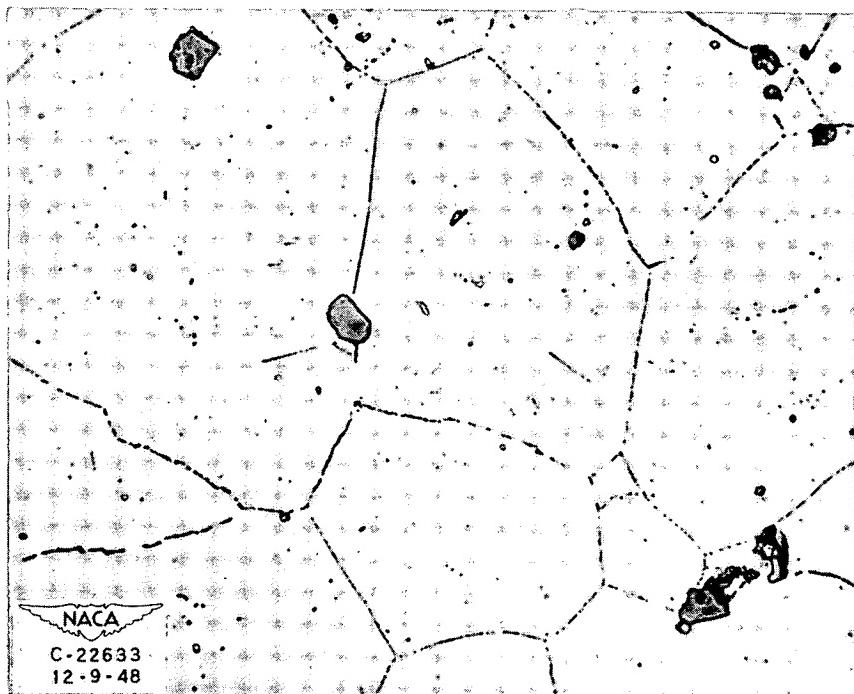
Figure 14. - Intercrystalline cracks in liner run for 16 hours and 40 minutes. Type-B liner; etchant, aqua regia and glycerine; condition, cracked during accelerated-life runs; magnification, X250. Incipient intergranular cracks formed at punched edge. Note small grains at edge. Cracks are lined with oxide scale, which does not show.

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(a) Not treated (dead soft).



(b) After heating at 900° F for 1 hour and air-cooling.

Figure 15. - Microstructure of dead-soft Inconel. Etchant, 10-percent sodium cyanide, electrolytic; magnification, X750.

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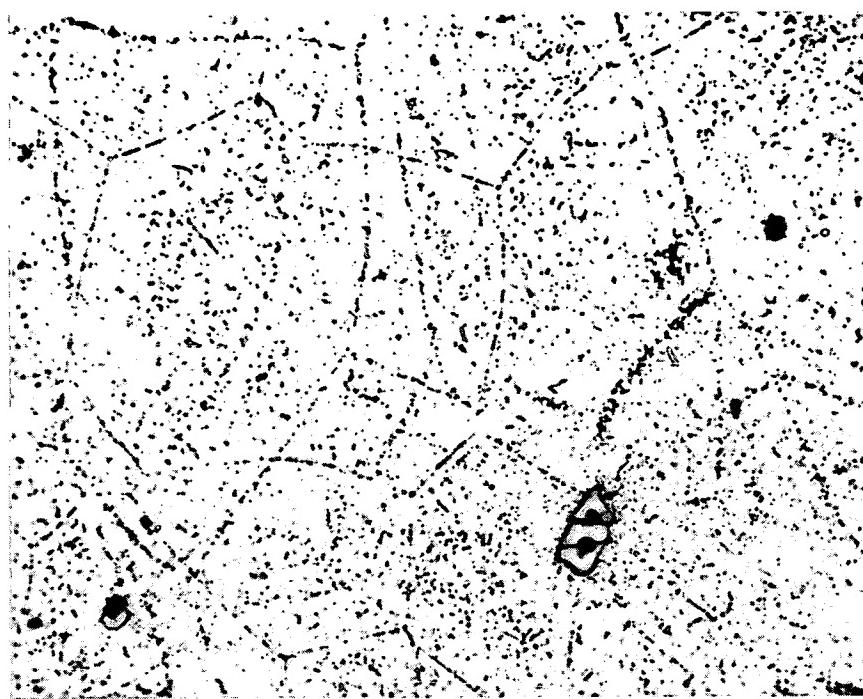
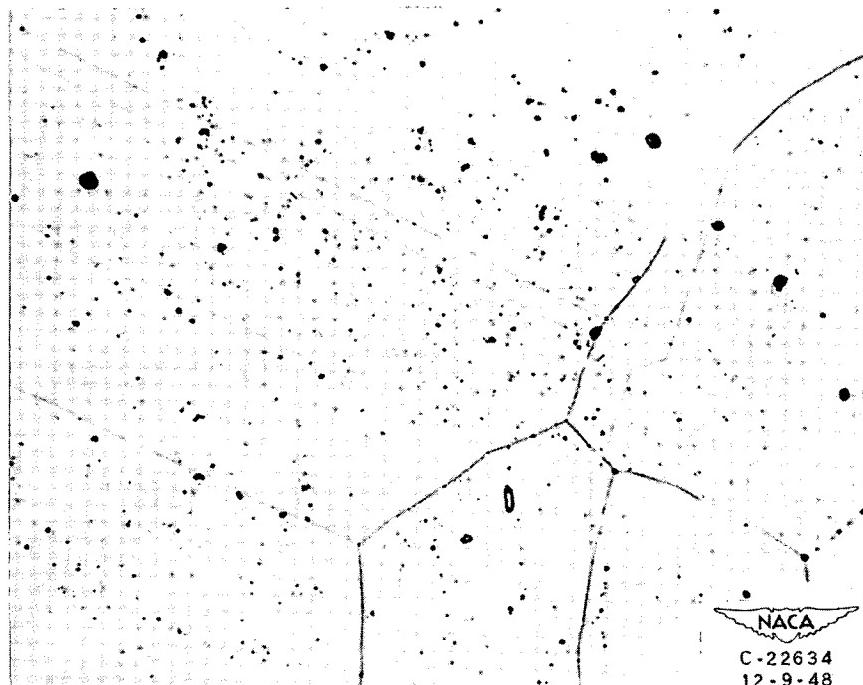
(c) After annealing at 1600° F for 2 hours and air-cooling.(d) After annealing at 2200° F for 2 hours and air-cooling.

Figure 15. - Concluded. Microstructure of dead-soft Inconel. Etchant, 10-percent sodium cyanide, electrolytic; magnification, X750.

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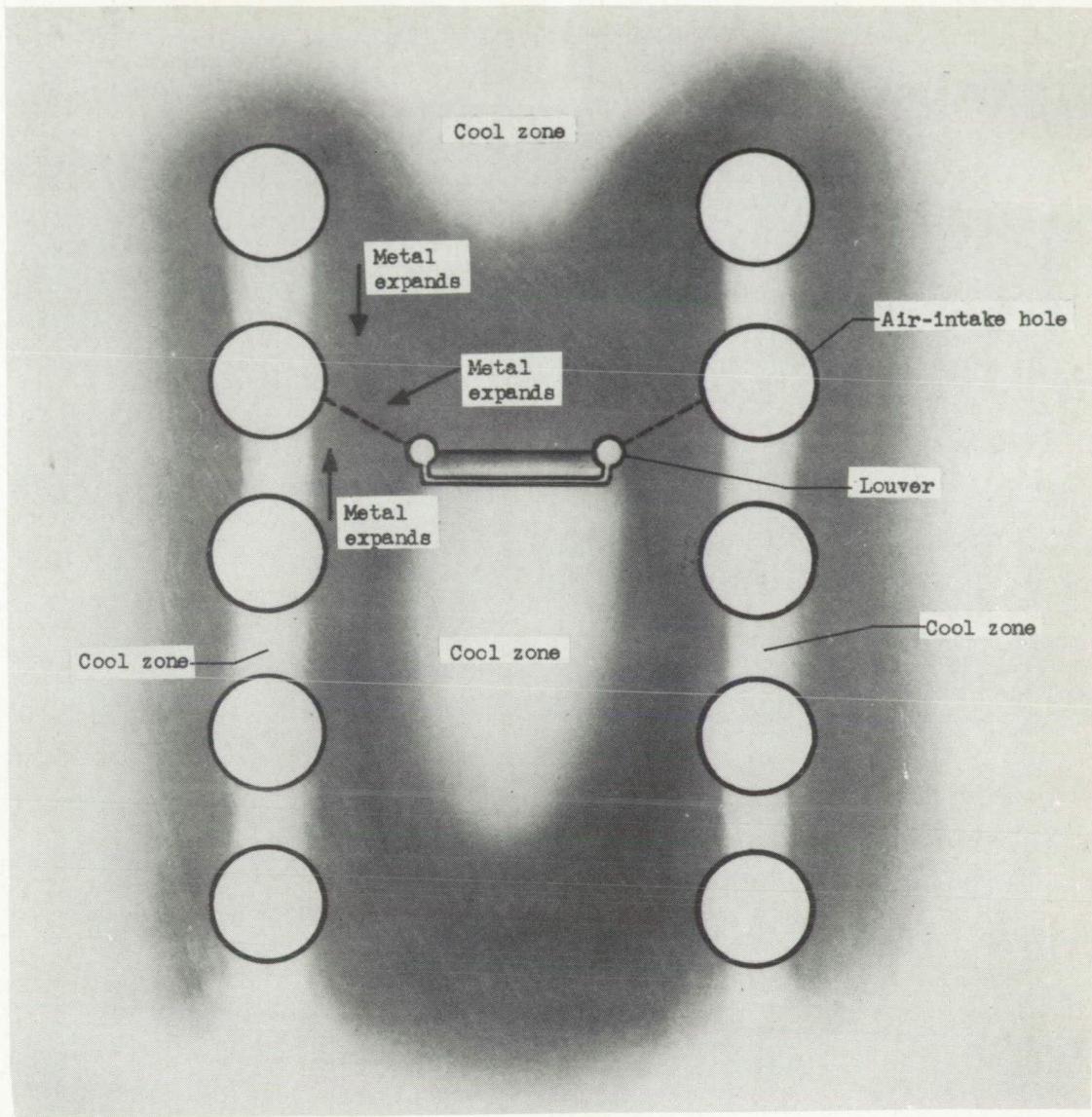


Figure 16. - Hot and cool zones about louver. Dashed lines indicate approximate location of buckles.

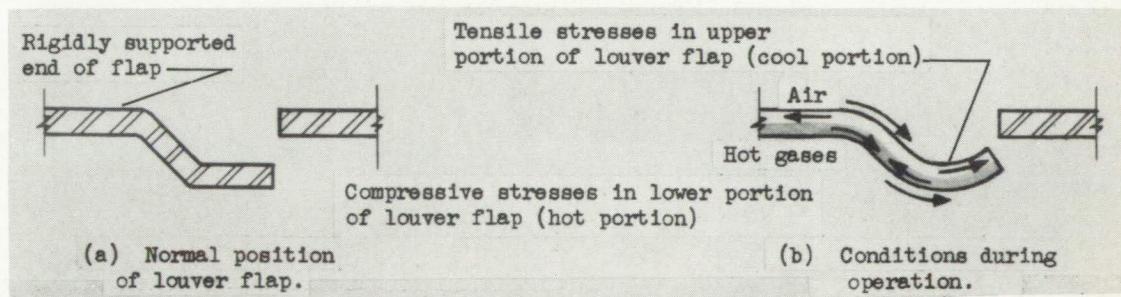


Figure 17. - Conditions in louver flaps.

